Explosion Dynamics of Core-Collapse Supernovae and the Multi-Messenger Signatures

Kei Kotake

(Fukuoka University)

with Tomoya Takiwaki (NAOJ) ,Takami Kuroda (NAOJ) ,
Kazuhiro Hayama (Osaka-city Univ.) ,
Yudai Suwa (Kyoto) , Ko Nakamura (NAOJ) , Wakana Iwakami (Waseda) ,
Masaomi Tanaka (NAOJ) , and Shio Kawagoe (Univ. Tokyo)

TAUP 2013
@ September Asilomer, Monterey

One slide for Gravitational Waves (GWs)

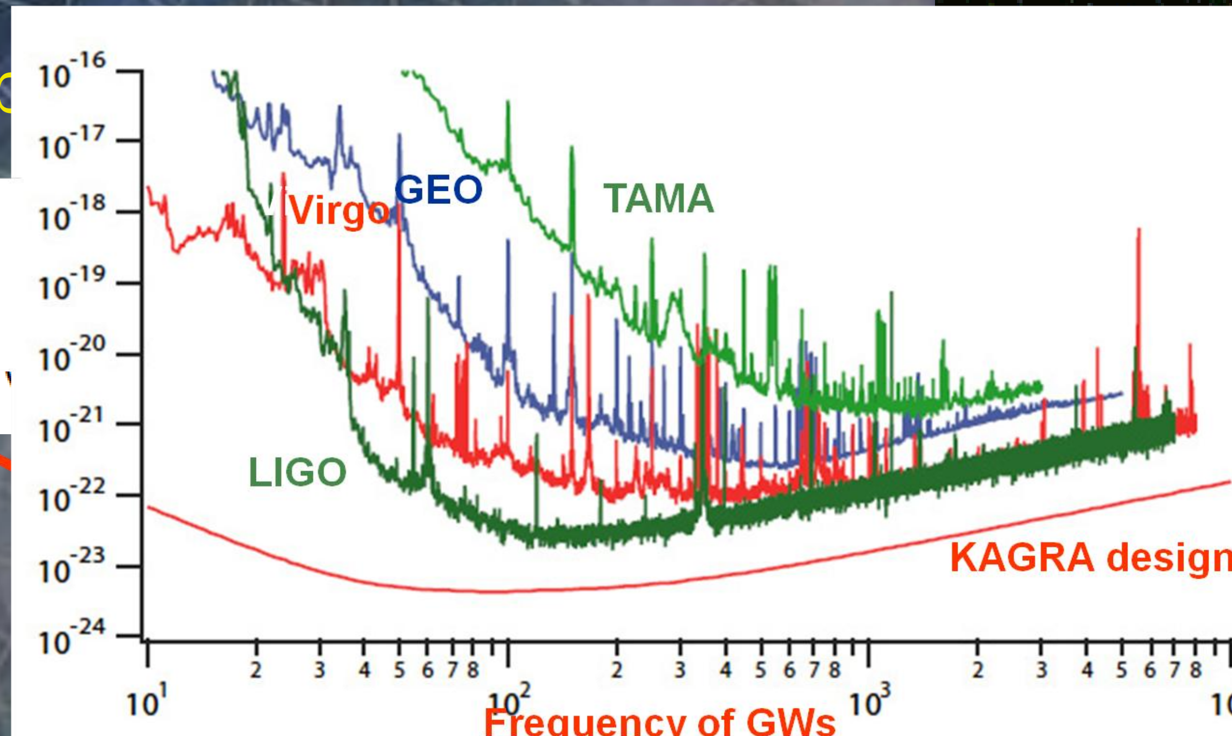
(see reviews in Kotake et al. (2006), Ott (2009), Fryer & New (2011), Kotake (2013))

☆ A back-of-envelop

GW amplitude

$$h_{ij} = \frac{2G}{c^4 R}\frac{\partial^2}{\partial t^2}Q_{ij} = \epsilon \frac{}{R}$$

$$h \sim 10^{-20}$$



✓CCSNe in our galaxy (~10 kpc) are the target of GWs

ϵ represents the degree of anisotropy.

What makes the SN-dynamics deviate from spherical symmetry ?

One slide for G

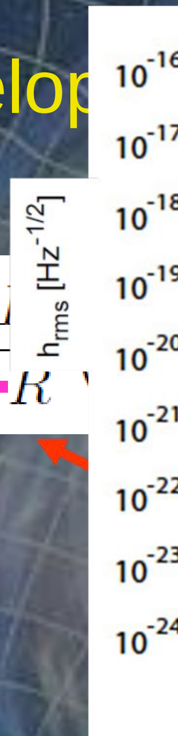
(see reviews in Kotake et

☆ A back-of-envelop

GW amplitude

$$h_{ij} = \frac{2G}{c^4 R}\frac{\partial^2}{\partial t^2} Q_{ij} = \epsilon \frac{}{R}$$

$h \sim 10^{-20}$



✓CCSNe in our galax

ϵ represents the d

What makes the SN-d
from spherical symme

Multidimensionality
(origin of anisotropy)

GW emission

Explosion dynamics

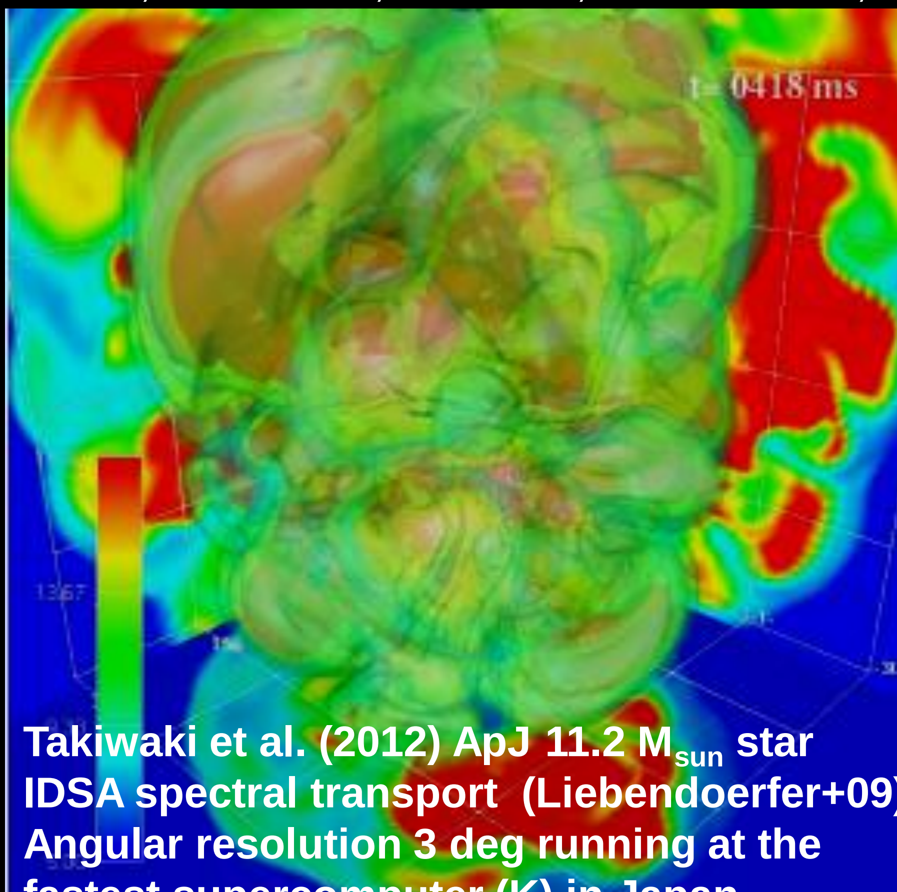
✓A dream of SN modellers is…
"To identify supernova mechanisms via GW/neutrino/EM observations ! "

✓ Theoretically, Need to understand the explosion physics/dynamics !

Current Status: Two Candidate Mechanisms

Neutrino-heating mechanism

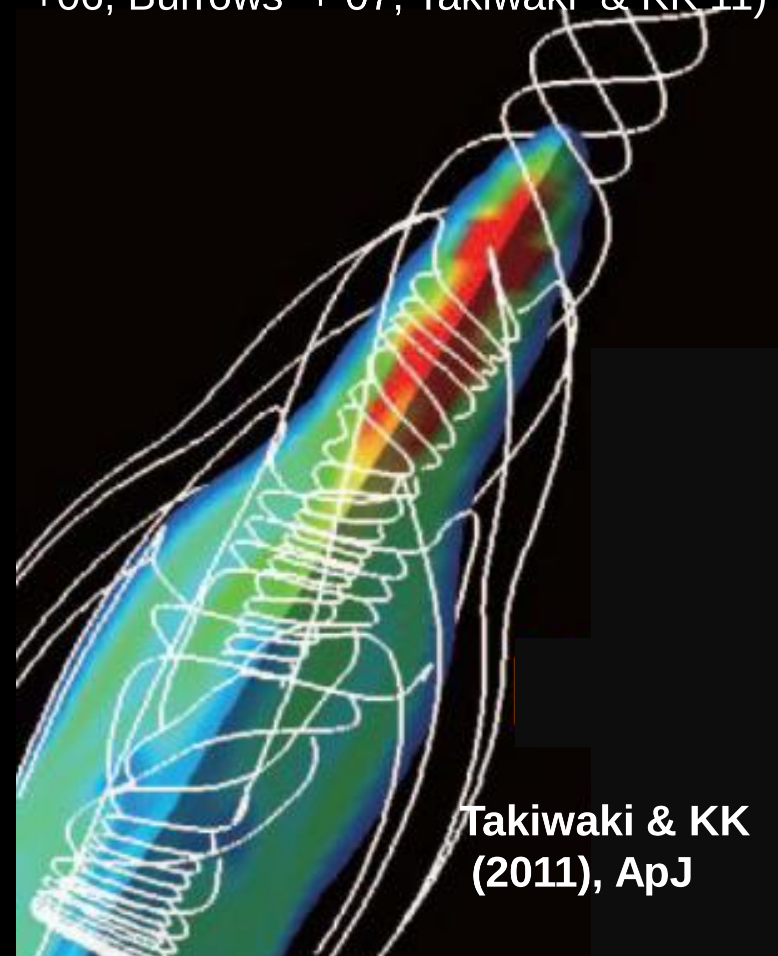
(Pioneered by Colgate & White (1966), Wilson(85)
see Marek & Janka 2009, Fernandez & Thompson 09
Ott+ 08, Bruenn+12,Suwa +09, Takiwaki + 12, 13)



Takiwaki et al. (2012) ApJ 11.2 M_{sun} star
IDSA spectral transport (Liebendoerfer+09)
Angular resolution 3 deg running at the fastest supercomputer (K) in Japan.

MHD mechanism

(Pioneered by Leblanc & Wilson (1970)
KK+04, 06 , Obergaulinger+06, Shibata +06, Burrows + 07, Takiwaki & KK 11)

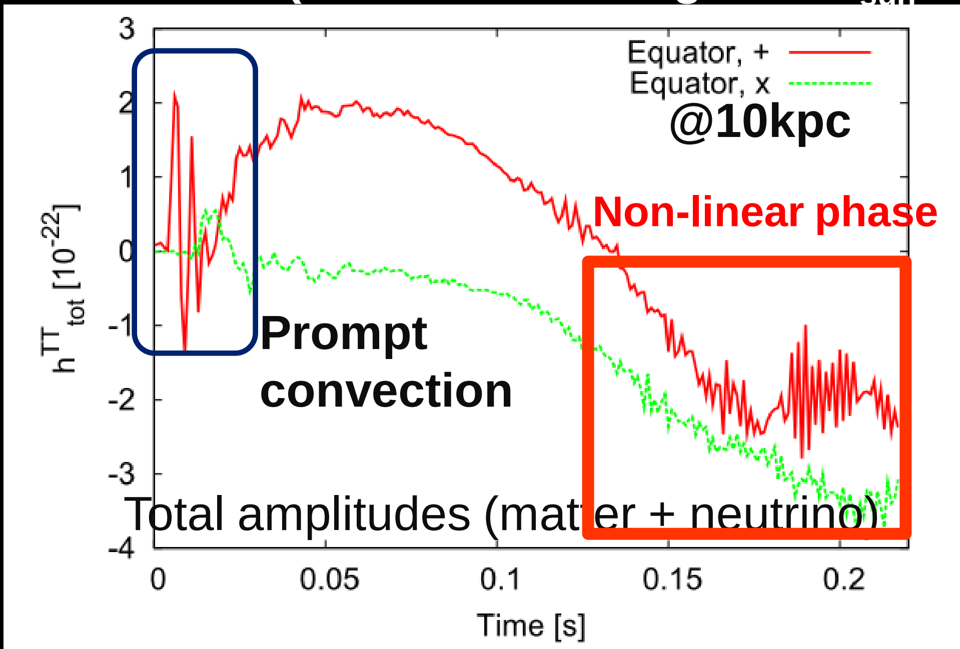


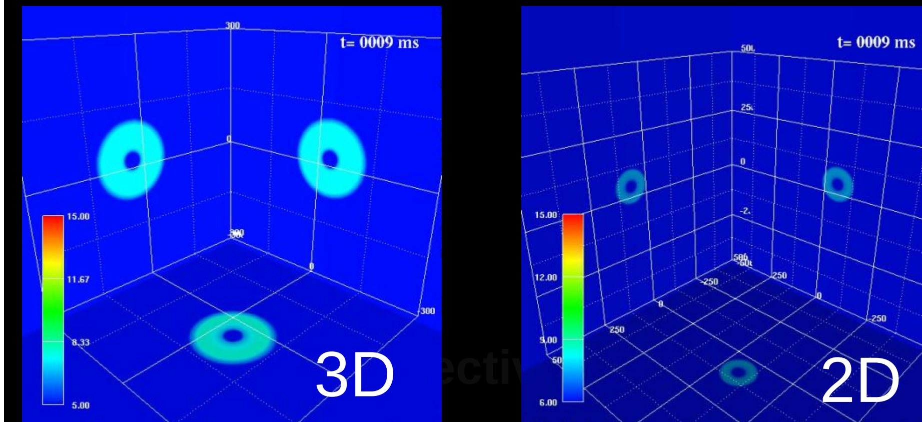
Takiwaki & KK (2011), ApJ

Gravitational waveform from self-consistent 3D model

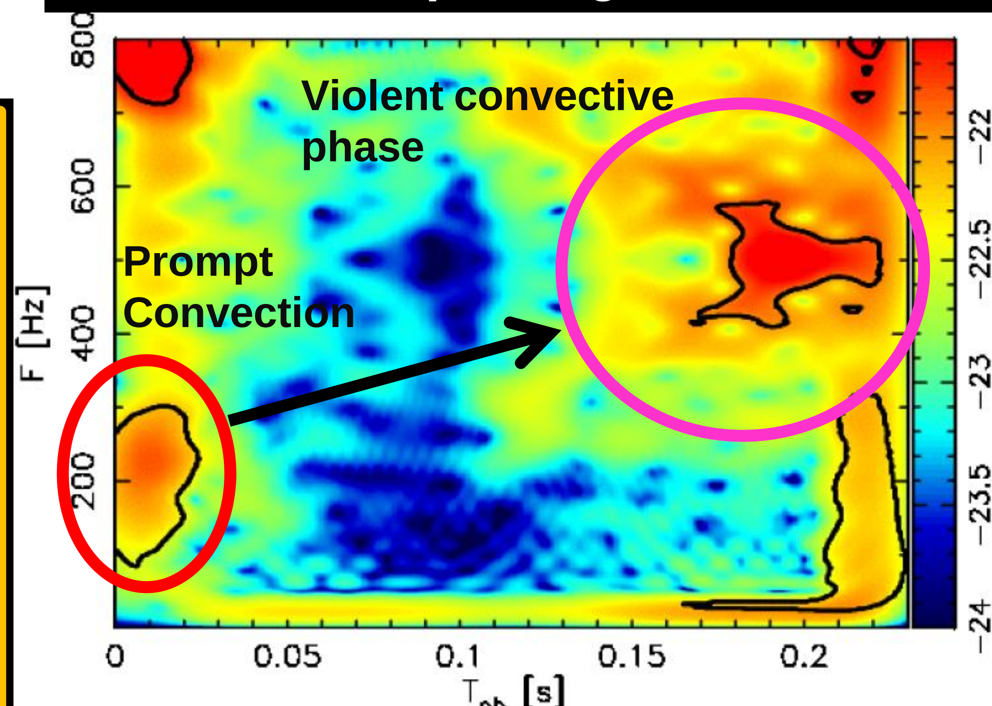
KK, Takiwaki, Suwa in prep.

Waveform (for a non-rotating 11.2 M_{sun} star)





GW spectrogram

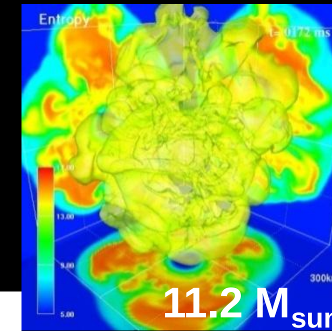


✓ Qualitatively: The evolution of the GW spectrogram is similar between 2D and 3D.
(2D: B.Mueller+(13), Yakunin+(09), e.g., Ott (2009), Kotake (2013) for reviews)

✓ Quantitatively: The GW amplitudes in 3D (one-order-of magnitude) smaller than in 2D.

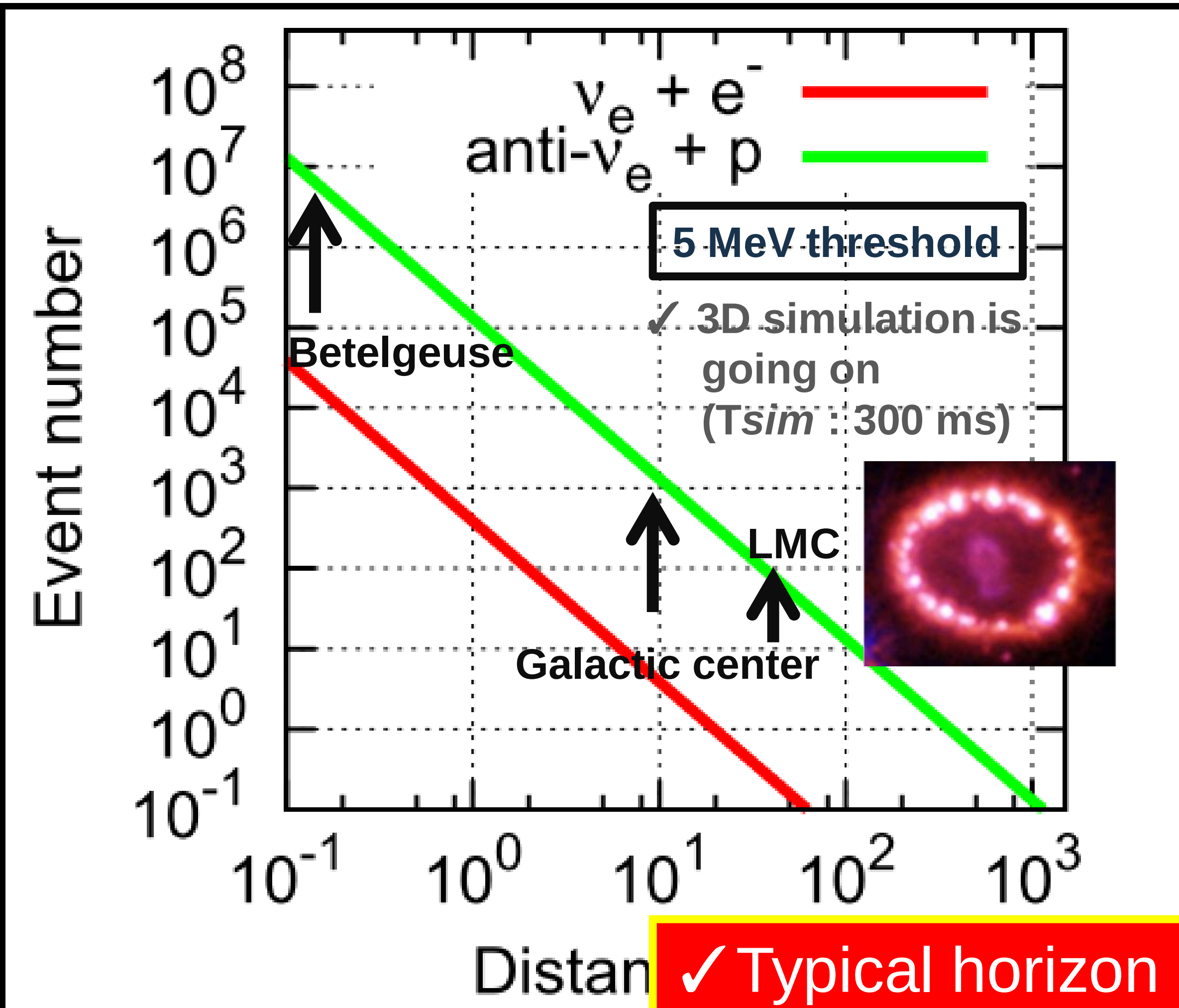
Expected number of ν events at Super-K

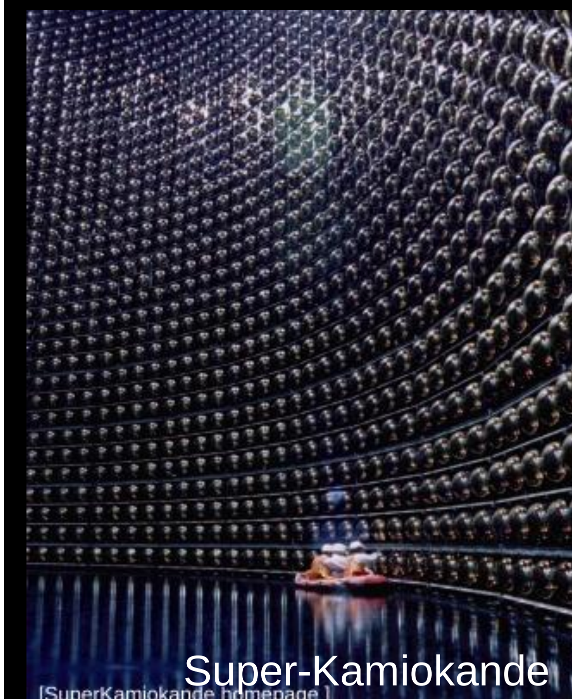
from our self-consistent 3D model (Takiwaki et al. 2013 in prep)



✓ **Inverted hierarchy (self-interaction: single-angle approx.)**

$$\sin^2 2\theta_{13} = 0.092$$





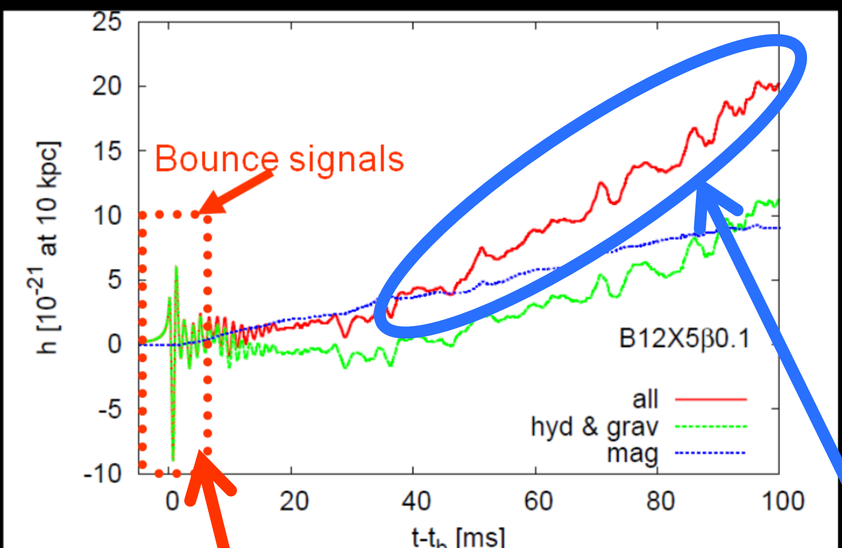
✓Typical horizon extends out to LMC.

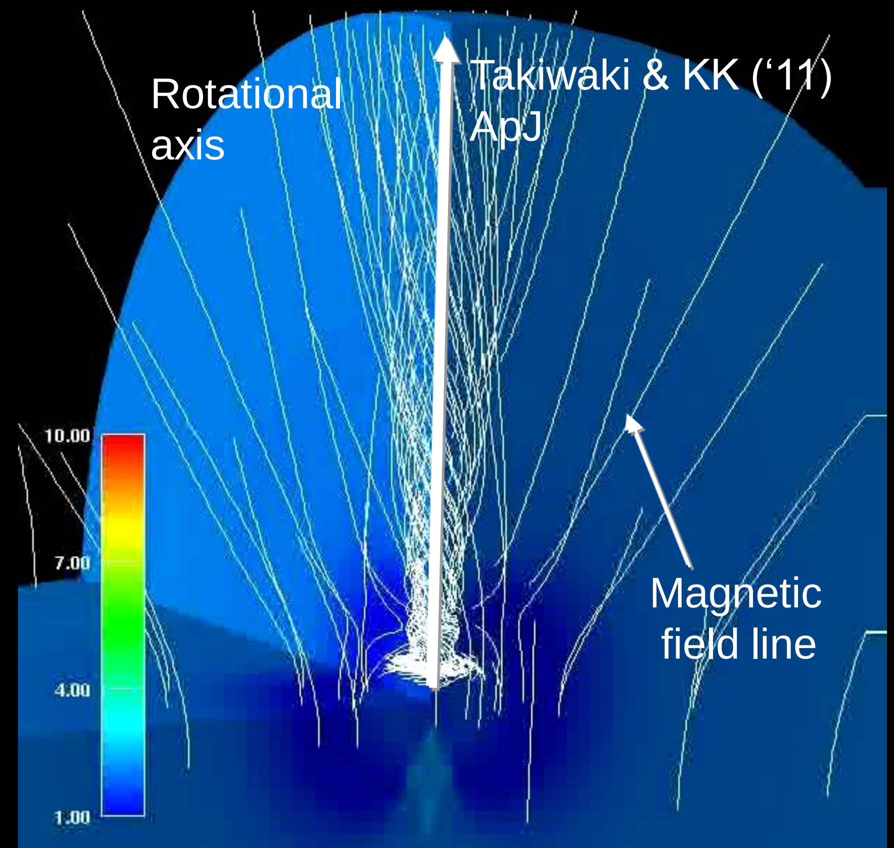
MagnetoHydroDynamic (MHD) mechanism

(e.g., LeBlanc Wilson !970, Symbalisty 1984, KK et al.04, Obergaulinger+08, Burrows+07, Shibata+06, Suwa+08)

✓ Works only when pre-collapse core has rapid rotation ($P_0 < 4$ s) and strong magnetic fields ($B_0 > 10^{11}$ G) ⇒ jet-like explosions

Gravitational waveform from MHD explosion





✓ Jets produce a quasi-monotonically increasing GW component after bounce !
(e.g., Obergaulinger et al. (2006) A&A)

(f_{GW} < 50 Hz hard to detect limited by seismic noise)

To accurately determine GWs near core bounce from rotationally-deformed compact PNS, 3D full GR simulations needed (e.g., Ott+07, see talk by Abdikamalov !)

GWs from rapidly rotating core: 3D full GR simulations with approximate ν transport

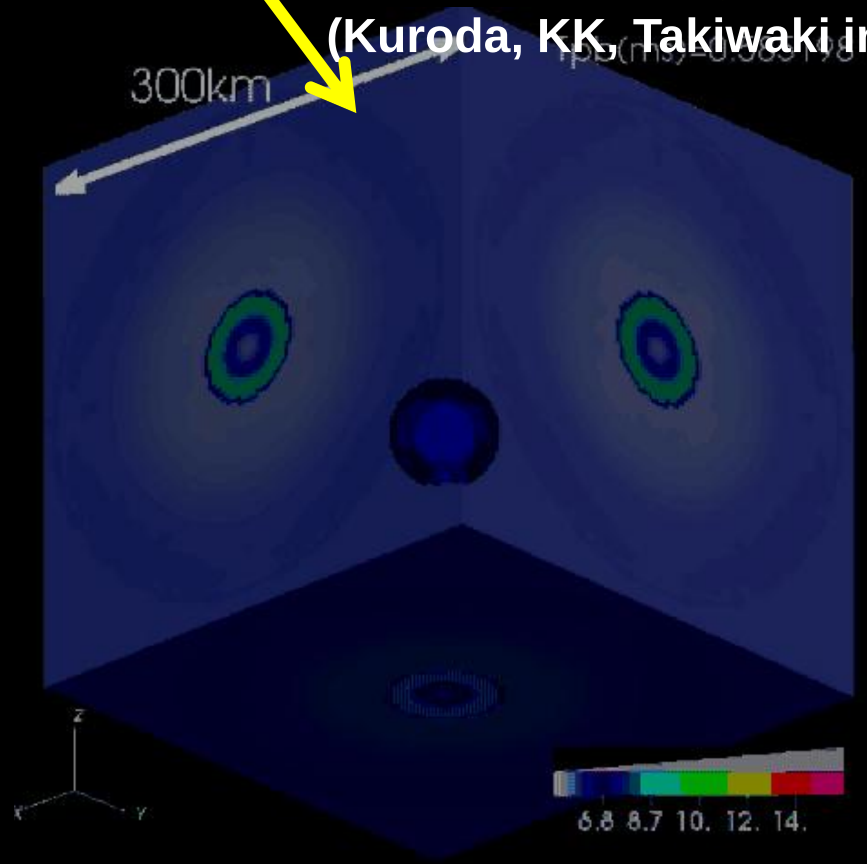
Kuroda, KK, Takiwai ('12) ApJ

✓The ray-by-ray approximation breaks down !
The Thorne's moment formalism implemented (Shibata+11).

✓ Mesh-refinement approach (δx = 450-600m. Similar to Ott+13)

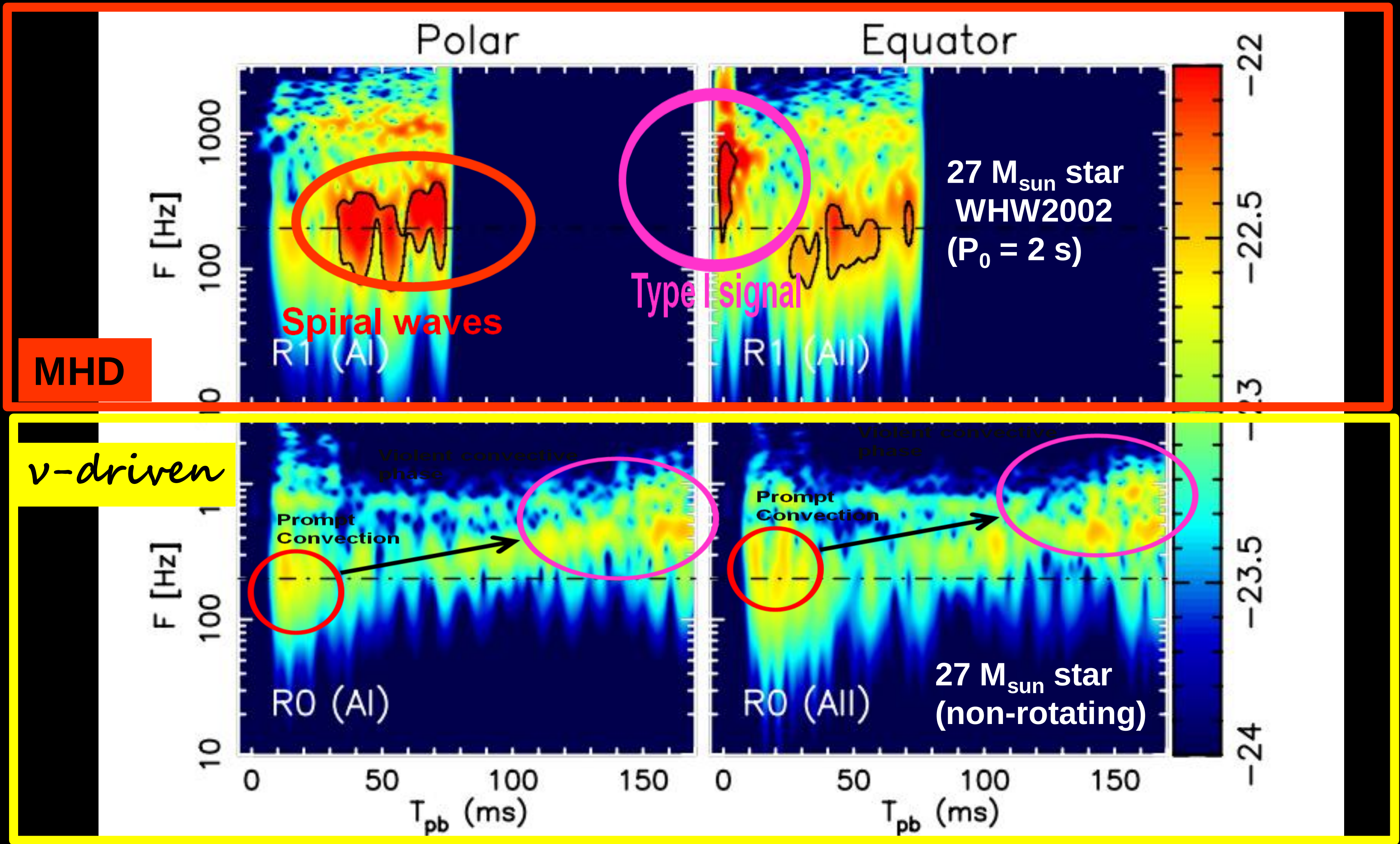
Rapidly rotating ($\Omega = \pi$ rad/s) and non-rotating 27 M_{sun} star

(Kuroda, KK, Takiwaki in prep)



Comparison between MHD vs. ν-driven mechanism

GW spectrogram (Kuroda, Takiwaki, KK in prep)



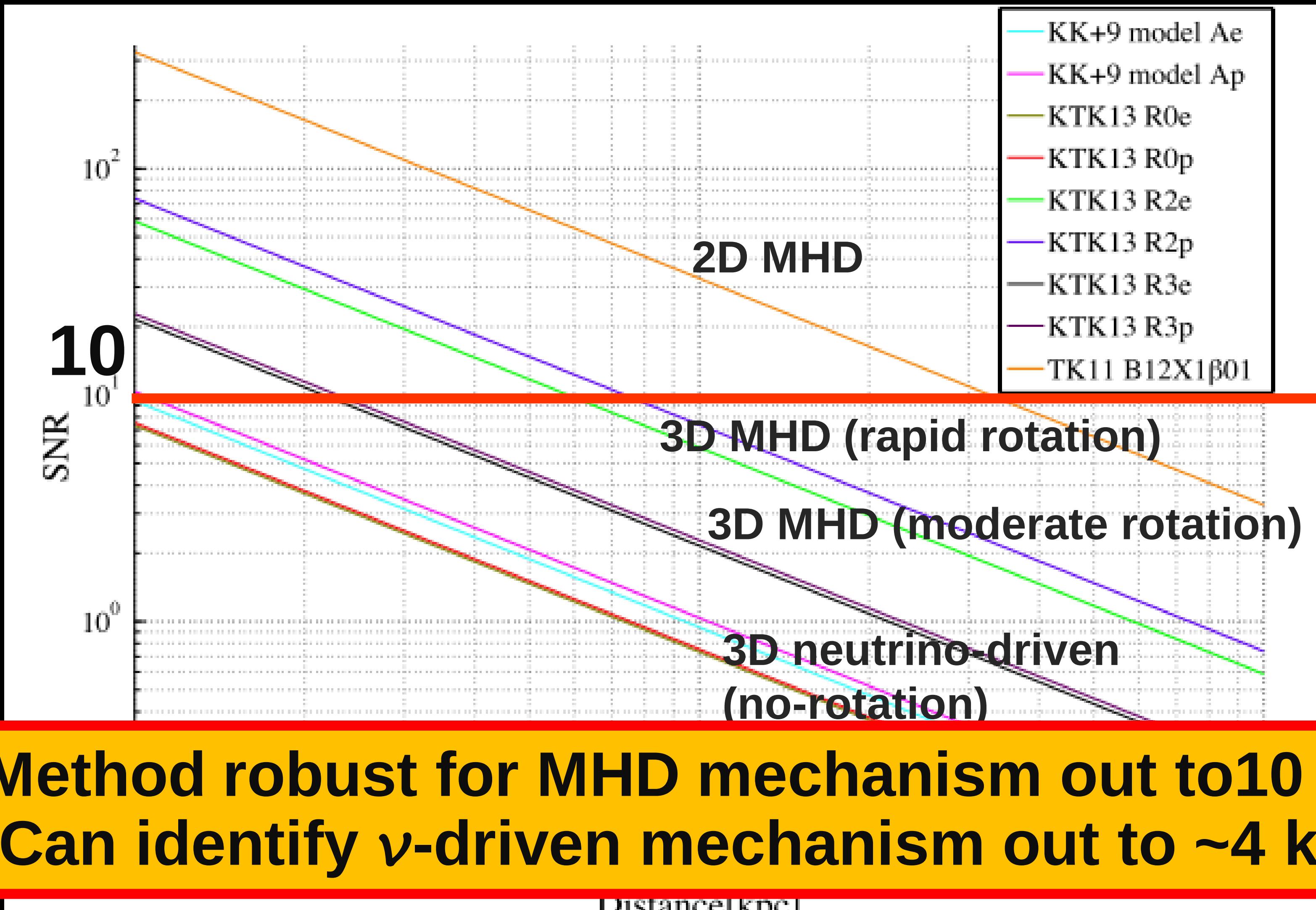
- The GW spectrogram so different : Excess-power method (Flanagan & Hughes '98)

Identifying SN mechanisms from Coherent Network Analysis

Hayama, Kuroda,Takiwaki, & KK (2013a) in prep

✓LIGOx2, VIGRO, KAGRA

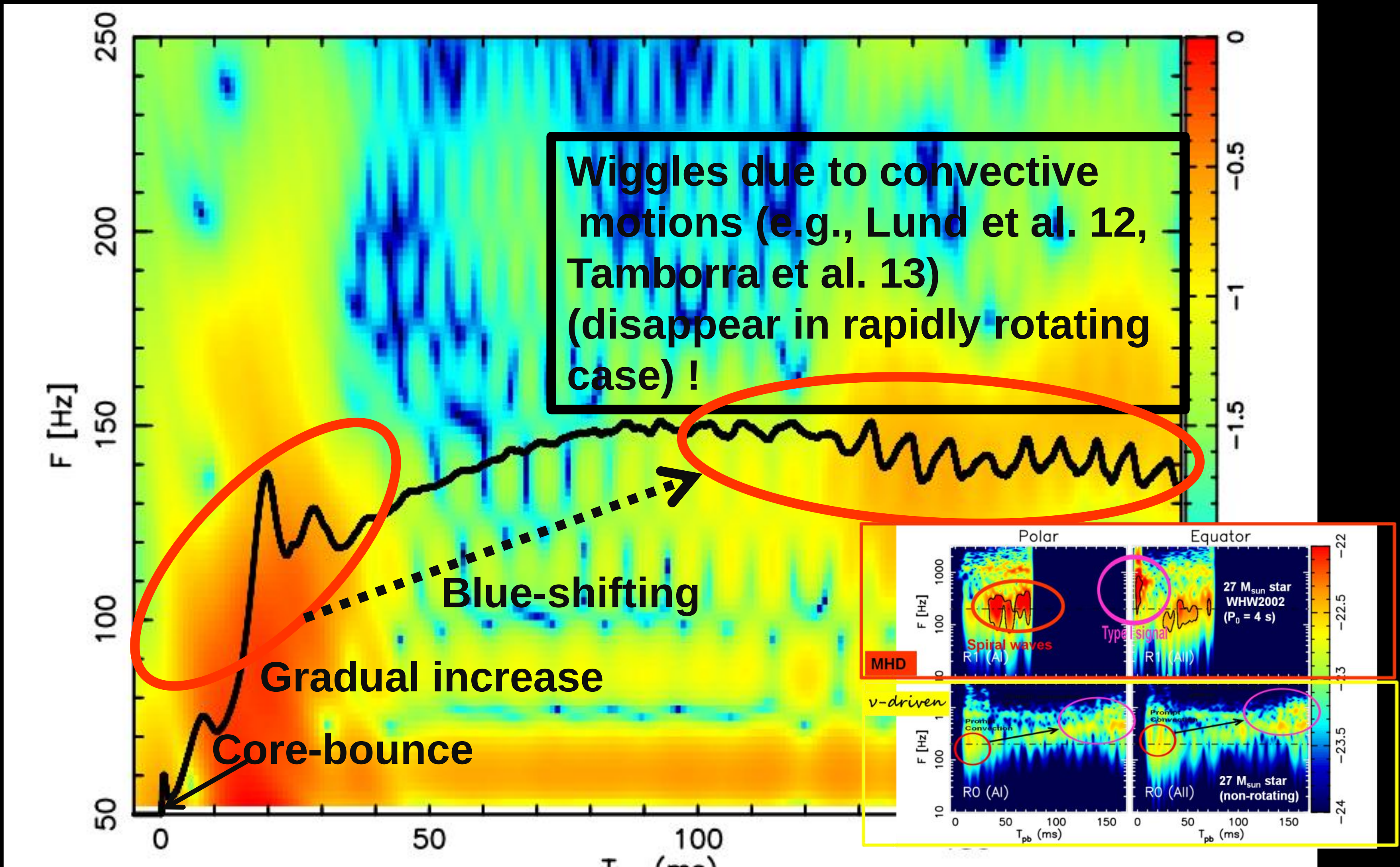
SNR (Signal-to-Noise) ratio as a function of source distance



✓Method robust for MHD mechanism out to10 kpc !
✓ Can identify ν-driven mechanism out to ~4 kpc.

Spectrogram of Neutrino ($\bar{\nu}_e$) luminosity for non--rotating 27 M_{sun} star

(Kuroda, KK, Takiwaki in prep)



Coincident analysis of GWs and neutrinos: helpful to pin-down the SN mechanisms

➤ More long-term simulations are needed ! (1000 ms/ (2 - 3 ms day) → 300 – 500 days !

Summary

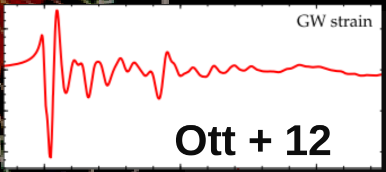
Neutrino-heating mechanism

✓The waveforms are different from models to models, because GWs from convection/SASI are of a stochastic nature governed by turbulent and chaotic fluid motions, non-linear hydrodynamics.

✓ But more importantly, the explosion dynamics is "commonly" imprinted in the GW spectrogram in both 2D and 3D models.

MHD mechanism (P_0 < ~ 4 s).

✓ Seen from equator, type-I waveforms are generically obtained.



✓ To determine the GW signatures seen from the pole, low T/|W| instability and spiral SASI modes play a crucial role (3D GR simulations are needed !)

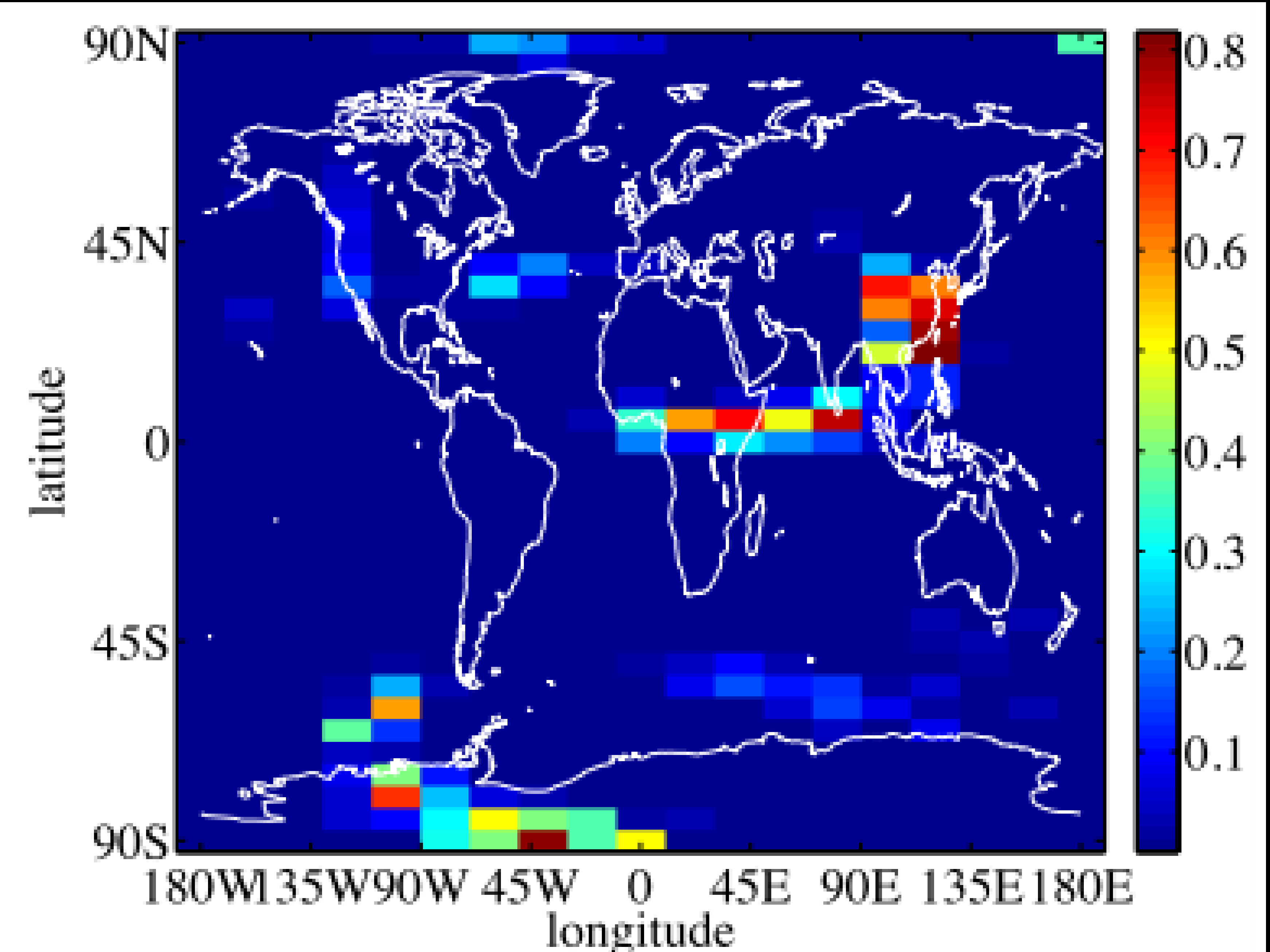
✓For detecting these signals, the coherent network analysis is expected to be robust out to ~10 kpc for the MHD mechanism and ~ 4 kpc for the neutrino-driven mechanism.

✓ A coincident analysis with neutrinos will make the false-alarm-rate smaller (> one order of magnitude). (Hayama, KK et al. in prep)

☆3D full GR simulations including neutrino transport are running (now!), which will update the theoretical predictions (very soon !)

"Coincident multi-messenger analysis will be the fi the long-standing supernova problem. "

Many thanks !



90N
45N
0
45S
90S
latitude
180W
135W
90W
45W
0
45E
90E
135E
180E
longitude
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1